SD-6942/S-97581

MICROFABRICATED BRAGG WAVEGUIDE

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Express Mail No.: EL026586509US

Microfabricated Bragg Waveguide

STATEMENT OF GOVERNMENT INTEREST

This invention was made with Government support under contract no. DE–AC04–94AL85000 awarded by the U. S. Department of Energy to Sandia Corporation. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

This invention relates to optical waveguides and, more particularly, to hollow waveguides based on optical confinement by Bragg reflection that are fabricated with integrated circuit (IC) technology.

Waveguiding of light is typically based on refractive index contrast for optical confinement. For example, the vast majority of optical fibers are dielectric fibers comprising a core of high refractive index material surrounded by a cladding of lower index material whereby light is guided within the fiber by total internal reflection of the guided light at the core-clad interface. In particular, silica-core fibers are ideal for propagation of telecommunications signals at the near-infrared absorption minimum of silica.

Conventional dielectric fibers can have disadvantages for specialized applications. Fiber attenuation can result from absorption and scattering of the guided light by the core material. Silica and most other materials become highly absorbing at longer wavelengths, limiting the far-infrared transmission through most solid-core fibers. Furthermore, Rayleigh scattering in solid core materials increases rapidly at shorter wavelengths. Dielectric fibers typically have small core-clad refractive index contrast and consequent large critical angle for total internal reflection. As a result, dielectric fibers can suffer large bending losses when the angle at which the light hits the core-clad interface falls within the critical angle at small bending radii. Thus, conventional dielectric fibers cannot bend light around sharp turns, important for optical integrated circuits and other microphotonic applications. The refractive index contrast of the waveguide can be improved with higher index semiconductor core materials, enabling tighter

bending radii. However, it becomes more difficult to effectively couple light into the waveguide when the refractive index of the core material is increased. This coupling problem can make the assembly and packaging of integrated microphotonic systems difficult.

Recently, interest has grown in hollow- and liquid-core waveguides, primarily for medical and industrial applications. With hollow-core waveguides, the solid core is replaced by a non-absorbing gas or vacuum. The cladding material generally has a refractive index greater than the core material such that the wave is guided by reflections at the core-clad interface. Attenuation due to core material absorption can be low and such hollow waveguides can have large damage thresholds and high power capacities due to the absence of a core material. Furthermore, hollow waveguides can have low insertion loss, since end reflections from a solid core are eliminated.

However, metal-clad hollow waveguides, in particular, can be leaky due to imperfect wall reflectivity resulting from absorption and diffuse scattering by the metal clad at infrared and visible wavelengths. Scattering due to surface roughness is further accentuated because reflections are at near-grazing incidence. Multiple imperfect reflections can result in large transmission losses, thereby favoring large cross-section hollow waveguides. Likewise, hollow waveguides can suffer large bending losses due to mode coupling and the increased number of reflections off of the outer and inner walls of the waveguide with tight bends. It has been observed that the reflectivity of metal-clad hollow waveguides can be improved by coating the internal metallic guide surface with a thin, less-conductive dielectric cladding layer. However, only relatively large dielectric-coated metal hollow waveguides have been fabricated. Furthermore, such dielectric-coated metal waveguides can still suffer relatively large bending losses and transmission losses due to interaction of the guided wave with the underlying metallic layer. Harrington *et al.* "Review of hollow waveguide technology," SPIE 2396, 4 (1995).

Bragg fibers, built on the principle of the cylindrical multilayer dielectric mirror, have been proposed for low loss broadband guiding of light in air.

Analysis has shown that confined modes can exist in a Bragg fiber comprising a low-index core (for example, air) surrounded by a cladding of alternating high- and low-refractive-index layers. Yeh *et al.* "Theory of Bragg Fiber," J. Opt. Soc. Am. 68, 1196 (1978). These Bragg fibers are predicted to have low transmission loss and can have a large single mode volume. Recently, the theory of the Bragg fiber has been extended to include omnidirectional waveguides that exhibit strong reflectivity over a range of incident angles with appropriate choice of dielectric layers, allowing for guiding light around sharp bends. Fink *et al.* "A Dielectric Omnidirectional Reflector," Science 282, 1679 (1998).

Waveguiding in a Bragg fiber comprising alternating thin layers of polymer and tellurium on the inside of a rubber tube has recently been demonstrated. Fink *et al.* "Guiding Optical Light in Air Using an All-Dielectric Structure," J. Lightwave Tech. 17, 2039 (1999). This large diameter Bragg fiber exhibited strong omnidirectional reflectivity and good transmission around a relatively small radius bend for guided light in the wavelength range of 10 to 15 micrometers. However, the Bragg fiber described by Fink *et al.* is not fabricated using IC technologies and, therefore, does not use semiconductor-compatible materials and is limited to guiding longer wavelength light.

Bragg waveguides, with multilayer dielectric cladding, may be attractive for microphotonic applications. However, a need remains for small diameter Bragg waveguide that can transmit light at wavelengths of use with optical integrated circuits and that can be fabricated with semiconductor-compatible technologies and materials.

The present invention comprises a microfabricated Bragg waveguide and a method for fabricating the Bragg waveguide. The microfabricated Bragg waveguide has a number of attractive features for use in microphotonics applications. It is designed to allow modest radiation losses for both TE and TM polarizations, thus leading to a waveguide of general utility. The increase in the mode size and low insertion loss afforded by the propagation of light in air may greatly improve coupling efficiency to optical components, a critical issue for integrated microphotonics. Coupling may also be improved resulting from the

absence end reflections, which can be a difficulty with silica fibers requiring highly polished end facets. Light propagation in an air-core waveguide may also reduce some material dispersion effects that are inherent with solid-core fibers. The microfabricated Bragg waveguide of the present invention can be fabricated with IC technologies using semiconductor-compatible materials. This enables material and fabrication flexibilities not possible with prior art Bragg fibers. For example, the microfabricated Bragg waveguides can have arbitrary cross-section and very small core size. The small core size enables guided waves with only a few modes. The reduced size further enables integration with microelectromechanical systems (MEMS) actuation schemes and smaller and less complex optical integrated circuits.

SUMMARY OF THE INVENTION

The present invention provides a microfabricated Bragg waveguide of semiconductor-compatible materials. The microfabricated Bragg waveguide can be a channel or fiber having a hollow core for the propagation of an optical guided wave therein. The Bragg waveguide further comprises a multilayer dielectric cladding disposed on at least one wall of the fiber or the inner wall of the channel, the cladding comprising at least one alternating layers of a first semiconductor-compatible dielectric material having a high index of refraction and a second semiconductor-compatible dielectric material having a lower index of refraction, such that the thicknesses of the alternating layers are carefully chosen to minimize radiation loss.

The present invention further comprises a method for fabricating a Bragg channel waveguide, comprising coating a top surface of a substrate with a mask layer of a structural material, forming an opening in the structural mask layer, etching a trench in the substrate through the opening in the structural mask layer, and coating the inner wall of the trench with a multilayer dielectric cladding.

The present invention further provides a method for fabricating a Bragg fiber, comprising forming a trench in a substrate, coating the inner wall of the trench with a first layer of a structural material, filling the structural material-lined

trench with a sacrificial material to leave an exposed deposit surface, coating the deposit surface of the sacrificial material with a second layer of the structural material, removing the sacrificial material to leave a hollow fiber in the trench, removing the substrate to leave a hollow fiber of the structural material, and coating at least one wall of the hollow fiber with a multilayer dielectric cladding.

Alternatively, the Bragg fiber can be fabricated by forming a mandrel of a sacrificial material, coating the surface of the mandrel with a multilayer dielectric cladding, and removing the sacrificial material to leave a hollow tube of the multilayer dielectric cladding.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form part of the specification, illustrate the present invention and, together with the description, describe the invention.. In the drawings, like elements are referred to by like numbers.

FIG. 1 shows a schematic illustration of a one-dimensional (1D) waveguide. FIG. 1a shows a 1D waveguide comprising a low-refractive-index core and a higher index clad. FIG. 1b illustrates a ray of light undergoing multiple reflections while propagating in a multilayer dielectric cladding of a 1D Bragg waveguide.

FIG. 2 shows field distributions for a plane electromagnetic wave propagating in a 1D Bragg waveguide with a multilayer dielectric cladding. FIG. 2a shows the field distribution for the TE_1 mode propagating in a 1D hollow Bragg waveguide with a Si/SiO_2 multilayer cladding. FIG. 2b shows the field distribution for the TM_1 mode propagating in a 1D hollow Bragg waveguide with a Si/SiO_2 multilayer cladding.

FIG. 3 illustrates a method to fabricate a Bragg channel waveguide using integrated circuit technology.

FIG. 4 illustrates a method to fabricate a Bragg fiber using a sacrificial mandrel.

FIG. 5 illustrates a method to fabricate a Bragg fiber using a sacrificial mold.

FIG. 6 shows a scanning electron micrograph (SEM) of a Bragg channel waveguide in a silicon substrate having a Si/SiN multilayer cladding designed to guide light with a wavelength of 1.55 μm. FIG. 6a shows a low magnification SEM of the Bragg channel waveguide. FIG. 6b shows a high magnification SEM of the multilayer dielectric cladding structure of the Bragg channel waveguide.

FIG. 7 shows a graph of transmission spectra for Bragg channel waveguides having a Si/SiN multilayer cladding constructed to a guide light with a wavelength of 1.65 μm.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1a shows a schematic illustration of a 1D waveguide comprising a core **110**, with refractive index n_{core}, surrounded by a clad **120**, with a higher refractive index n_{clad}. For the case wherein the wavelength λ of the guided wave is much smaller than the separation 2d between the cladding plates **120**, Nishihara *et al.* derived the following analytical expressions for the attenuation α of the transverse electric (TE) and transverse magnetic (TM) modes in a 1D waveguide with air as the core material:

$$\alpha = m^2\lambda^2 \operatorname{Re}(1/(\nu^2 - 1)^{1/2})/16d^3 \quad \text{for } TE_m \text{ modes, and}$$

$$\alpha = m^2\lambda^2 \operatorname{Re}(\nu^2/(\nu^2 - 1)^{1/2})/16d^3 \quad \text{for } TM_m \text{ modes}$$

where m is the mode number and ν is the complex index of refraction of the clad material. H. Nishihara *et al.* "Low-loss parallel-plate waveguide at 10.6 μm," Appl. Phys. Lett. 25, 391 (1974). These expressions show that the attenuation is proportional to the squares of the mode number and the wavelength of the guided light. In general, losses increase rapidly with smaller waveguides, as the attenuation is inversely proportional to the cube of the clad separation. As a result, most metal-clad hollow waveguides have diameters of order 1 mm or larger. TE modes are seen to have less attenuation than TM modes with the same mode number, because $\nu^2 > 1$. For light of wavelength 1.55 μm propagating in a simple 1D silicon-clad hollow waveguide with air as the core

110, silicon as the clad **120**, and a 10 μm separation distance, the propagation losses for the lowest order mode range from 30 dB/cm for the TE mode, to 340 dB/cm for the TM mode. Losses of this magnitude make this simple waveguide impractical for most applications.

These losses can be reduced by coating the clad **120** with a multilayer dielectric cladding **100**, comprising alternating layers of high- and low- refractive index dielectric materials, wherein the cladding layer thicknesses are carefully chosen so that multiple reflections of rays reentering the core **110** add constructively and those constituting radiation loss to the clad **120** approximately cancel.

FIG. 1b shows a multilayer dielectric cladding **100** comprising a first cladding layer **101** of first dielectric material, having a refractive index n_1 and thickness t_1, and a second cladding layer **102** of second dielectric material, having a lower refractive index n_2 and thickness t_2. The multilayer dielectric cladding **100** can further comprise alternating interior cladding layers of the high-index dielectric material **103** and the low-index dielectric material **104**. Consider a guided ray **160** with wavenumber k_0 propagating in the hollow core **110** that impinges on the surface of the first cladding layer **101** at glancing incidence (because of the core diameter being many wavelengths in size). A refracted ray **170** is launched in the first cladding layer **101** at a critical angle θ. The refracted ray **170** subsequently undergoes two reflections, one from the low-index second cladding layer **102** and one at the core interface, generating the outgoing ray **180**. Leakage of the guided ray **160** from the core **110** will be a minimum when this outgoing ray **180** and the refracted ray **190** resulting from that portion of the guided ray **160** that propagates a further distance **l** down the core **110**, interfere destructively. Equalizing the optical paths of the guided **160** and refracted **170** rays, the condition for destructive interference of the radiated rays **180, 190** is given by:

$$k_0 l = 2k_0 n_i s + j\pi + (2N + 1)\pi$$

where N is an arbitrary integer, k_0 is the propagation constant $2\pi/\lambda_0$, and j accounts for the phase shift of π radians that may occur as a result of the two

reflections described above. J. D. Jackson, Classical Electrodynamics, John Wiley and Sons, Inc., NY, pp219-220 (1962). This same equation applies to radiation propagating outwards in each of the other cladding layers of the multilayer dielectric cladding **100**, provided that the parameters N and j are correctly chosen. The result is an equation for the optimum thickness t of each cladding layer.

For TE-polarized light, no net phase shift occurs, and we take N=-1 so that all layer thicknesses are predicted to be one-quarter of the wavelength of light in the respective layer (a so-called quarter wave stack). This corresponds to the stack design employed by Fink *et al.* cited above and is near-optimum for TE polarization. However, for TM-polarized light there is an extra phase shift at the core interface reflection so that we must take j=1 and the predicted layer thickness of the first cladding layer **101** is one-half wave. Therefore the optimum thickness for the first cladding layer **101** is different for different polarizations. But the common case of linear polarization will result in light interaction at the waveguide boundary that is TE-like at two opposite sides and TM-like at the other two. Thus, a waveguide design that is highly lossy for either polarization will be lossy for linear polarization, and thus will be of limited usefulness. It can be shown that the stack design consisting of quarter-wave thicknesses throughout is highly lossy for TM polarization, and so is unsuitable for many microphotonic applications. The modified stack design wherein the first cladding layer **101** is half-wave experiences modest losses for TE polarization (and of course very low loss for TM polarization). If the thickness of the first cladding layer **101** is slightly below the half-wave thickness, the TE loss is seen to decrease dramatically with only a modest increase in TM loss. The above condition for destructive interference will provide cladding layer thicknesses that result in a good overall stack design, resulting in a waveguide that works well at all polarizations, and is an important feature of the present invention. Stack designs for minimum radiation loss for waveguides of arbitrary cross-section can be obtained using the above principles with numerical models that are known to those in the optical design art.

For a microfabricated Bragg waveguide, the cladding layers can be made of silicon-based materials that have sufficiently high refractive index contrast for good optical confinement and are compatible with silicon integrated circuit processing technologies. These silicon-based materials comprise, for example, silicon nitride (SiN), polycrystalline silicon (poly-Si), silicon dioxide (SiO_2), silicon oxynitrides (SiO_xN_y), and silicon carbide (SiC).

As an example of the present invention, consider a guided wave of wavelength $\lambda = 1.55$ μm propagating in a Bragg waveguide having a Si/SiO_2 multilayer cladding **100** comprising alternating cladding layers of poly-Si ($n_{Si} = 3.5$) and SiO_2 ($n_{SiO2} = 1.46$). The thicknesses of the cladding layers for minimum loss can be 0.22 μm for the first cladding layer **101** of poly-Si, 0.36 μm for the second cladding layer **102** of SiO_2 and the interior SiO_2 cladding layers **104**, and 0.11 μm for the remaining interior poly-Si cladding layers **103**. Alternatively, the multilayer dielectric cladding **100** can comprise, for example, alternating layers of poly-Si and SiN ($n_{SiN} = 2.0$ at $\lambda = 1.55$ μm) or SiN and SiO_2. For a SiN/SiO_2 multilayer cladding **100** comprising SiN as the high-index material, the first cladding layer **101** of SiN can have a thickness of 0.42 μm and the interior SiN cladding layers **103** can have thicknesses of 0.22 μm.

FIG. 2a shows the magnetic field amplitude profile calculated using a 1D finite difference model for the TE_1 mode of light with wavelength $\lambda = 1.55$ μm propagating in a 1D Bragg waveguide with a hollow core and the Si/SiO_2 multilayer cladding **100** described above. The field dies away within about four cladding layer periods. The calculated attenuation for the TE_1 mode in this Bragg waveguide is only 0.2 dB/cm, more than an order of magnitude less than for the silicon-clad hollow waveguide.

Fig. 2b shows a similar field distribution for the TM_1 mode. The loss for the TM_1 mode is higher, about 3 dB/cm, but still substantially less than with the silicon-clad hollow waveguide. The losses for the Si/SiO_2 Bragg waveguide are less than for the silicon-clad hollow waveguide because of the higher reflectivity of the multilayer dielectric cladding **100** and consequent lower optical energy loss to radiation.

The Bragg waveguide of the present invention can be fabricated with integrated circuit technologies. Both channel and fiber waveguides can be fabricated according to the methods of the present invention.

FIG. 3 illustrates a method to fabricate a Bragg channel waveguide **300**. The Bragg channel waveguide comprises a trench **318** having a hollow core embedded in a substrate **314**, with a multilayer dielectric cladding **100** coated on the inner wall of the trench **318**. The Bragg channel waveguide **300** may be useful for guiding light passively in an integrated optical circuit. For example, the Bragg channel waveguide **300** may be of use with passive components such as splitters, combiners, resonators, couplers, and arrayed waveguide gratings.

The method for fabricating the Bragg channel waveguide **300** comprises coating a top surface of a substrate **314** with a mask layer **312** of a structural material, forming an opening **316** in the structural mask layer **312**, etching a trench **318** in the substrate **314** through the opening **316** in the structural mask layer **312**, and coating the inner wall of the trench **318** with a multilayer dielectric cladding **100**. Although the fabrication of a silicon-based Bragg channel waveguide **300** is described, the waveguide can be made of other semiconductor-compatible materials, such as materials based on group III-V and group II-VI compounds.

In FIG. 3a, the thin mask layer **312** of the structural material can be deposited on the substrate **314**. The substrate **314** can be single crystal silicon. For example, the structural material can be SiN or SiN/SiO_2. For example, a SiN mask layer **312** can be deposited by low pressure chemical vapor deposition (LPCVD) from dichlorosilane ($SiCl_2H_2$) and ammonia (NH_3) at about 800°C. For example, the structural mask layer **312** can be about 0.8 μm of SiN and 0.6 μm SiO_2 of in thickness.

In FIG. 3b, a slot **316** can be opened in the structural mask layer **312** by patterned etching. The SiN mask layer **312** can be patterned by reactive ion etching with a CHF_3-based plasma through a photoresist. The etch slot **316** can be wide enough to provide for the passage of etchants to form the underlying trench **318**. The etch slot **316** can be about 2 μm wide. The etch slot **316** can be

of the length of the trench **318** and can be shaped to provide arbitrary trench configurations. For example, the etch slot **316** can be configured as a "Y" to provide a waveguided optical splitter. The etch slot **316** can have larger inlet openings (not shown) at spaced intervals for the later introduction of gases into the trench **318** to deposit the cladding layers.

The trench **318** can be formed by selective etching of the substrate **314** through the etch slot **316** to form an overhanging mask layer of the structural material. The etch can be an isotropic etch, whereby the structural mask layer **312** is undercut to form a half-cylindrical trench **318**. For SiO_2 or SiN mask layers **312**, isotropic dry plasma etching with a fluorine-based etchant, such as SF_6 or NF_3, can be used to form the half-cylindrical trench **318** in the silicon substrate **314**. Alternatively, trenches **318** with other geometric cross-sections can be formed by appropriate choice of etchant, etch conditions, and substrate. For example, the trench **318** can be made to have parallelogram or triangular cross-section by anisotropic etching. The geometric cross-section can also be made to vary in the propagation direction of the guided optical wave.

In FIG. 3c, one or more thick layers **320** can be blanket deposited over the masked substrate and in the etch slot **316** to seal off the etch slot **316** to prevent leakage of the guided light from the channel Bragg waveguide **300**. The thickness of layer **320** can be slightly greater than one-half of the width of the etch slot **316**, or about 1-2 μm. The thick layer **320** can be poly-Si deposited by CVD. A layer of thermal oxide (not shown) can be grown on the poly-Si layer **320** to smooth the sidewalls of the trench **318**.

In FIG. 3d, the multilayer dielectric cladding **100** can be built up from the thick layer **320** on the inner wall of the trench **318** by alternating successive depositions of the concentric cladding layers to form the channel Bragg waveguide **300**. The reactant and carrier gases for chemical vapor deposition of the multilayer dielectric cladding **100** can be introduced into the trench **318** through the spaced gas inlets (not shown). The spacing of the gas inlets can be chosen to provide for uniform conformal coverage of the multilayer dielectric cladding **100** throughout the length of the sealed trench **318**. Since the multilayer

dielectric cladding **100** is built up from the inner wall of the trench **318**, only one cladding layer is added for each process step.

For example, the multilayer dielectric cladding **100** can comprise alternating layers of high-refractive-index poly-Si and low-index SiN. Alternatively, the multilayer dielectric cladding structure **100** can comprise Si/SiO_2, SiN/SiO_2, or other combinations of silicon-based materials. The cladding layer thicknesses can be chosen to satisfy the condition for minimum radiation loss at the wavelength of the guided optical wave. Therefore, for a guided optical wave of 1.55 mm wavelength in a Si/SiN waveguide, the poly-Si first cladding layer **101** can have a thickness of about 0.22 μm, the poly-Si interior cladding layers **103** can have thicknesses of about 0.11 μm, and the lower index SiN cladding layers **102**, **104** can have thicknesses of about 0.22 μm. Bragg waveguides for guided waves having alternative wavelengths can be fabricated by depositing a multilayer dielectric cladding **100** with cladding layer thicknesses satisfying the condition for minimum radiation loss at that desired wavelength. Cladding layers from about 10 nm to 1 μm thickness can be deposited by the above method, enabling guided light of a wide range of optical wavelengths.

Poly-Si can be deposited by LPCVD from silane (SiH_4) at 550 °C. Poly-Si is highly conformal, so that the spacing of the gas inlets can be large. SiN can be deposited by LPCVD from $SiCl_2H_2$ and NH_3, and is also highly conformal, but can have high stress. The high stress can limit the SiN layer thickness. CVD SiO_2 has poorer step coverage than poly-Si, necessitating a closer spacing of the gas inlets for a conformal coating of SiO_2 along the length of the trench **318**. For some applications, better step coverage may be preferred. For these applications, the SiO_2 layer can be grown by depositing an excess of poly-Si, followed by partial thermal wet oxidation of the poly-Si layer by reaction with oxygen in a moist environment at high temperature. For example, for the relatively uniform CVD of SiO_2 within a 10 μm diameter trench **318**, the gas inlets can be spaced about 400-1600 μm apart, depending on the deposition materials and conditions.

Alternatively, the Bragg waveguide can be a hollow fiber. The Bragg fiber comprises a free-standing fiber, having a hollow core, coated with a multilayer dielectric cladding **100** on the inner and/or outer wall of the hollow fiber.

The method for fabricating a Bragg fiber comprises forming a mold or mandrel of a sacrificial material, coating the mold or mandrel with a multilayer dielectric cladding **100**, and removing the sacrificial material to leave a free-standing hollow tube of the multilayer dielectric cladding **100**. Although the fabrication of a silicon-based Bragg fiber for 1.55 μm wavelength light is described below, the fiber can be made of other semiconductor-compatible materials, such as materials based on group III-V and group II-VI compounds. Also, the multilayer dielectric cladding **100** can be constructed to guide light of other wavelengths.

FIG. 4 illustrates an exemplary method for fabricating a Bragg fiber **400** wherein the multilayer dielectric cladding **100** is deposited on the exterior surface of a sacrificial mandrel **412** and the mandrel **412** is subsequently removed by selective etching to leave the Bragg fiber **400** having a hollow core. The sacrificial mandrel **412** can comprise a suspended structure, or beam, fabricated by techniques known to those in the MEMS art.

In FIG. 4a is shown a beam **412** suspended from a substrate **414**. For example, a rectangular beam **412** can be formed from {111} crystalline silicon by bulk micromachining methods as disclosed in U.S. Patent 6,020,272 to Fleming, which is incorporated herein by reference. The micromachining method disclosed by Fleming comprises forming a patterned mask layer (not shown) on the major surface **416** of the {111} silicon substrate followed by anisotropic dry etching down the silicon substrate through the patterned mask layer to a first etch depth that defines the bottom **418** of the beam **412**. A protective layer (not shown) is then deposited on the sidewalls **420** of the beam **412** exposed by the etching. The anisotropic etching is then continued down to a second etch depth that defines the remaining portion **422** of the top surface of the substrate **414**. The substrate **414** is then lateral undercut between the first and second etch depths with an anisotropic wet etchant that terminates etching upon reaching a

plurality of {111} crystal planes of the silicon substrate **414**, thereby forming a substantially planar bottom surface **418** that is substantially parallel to the upper surface **424** of the beam **412**. After the undercutting etch step, the patterned mask layer and the protection layer can be removed. The beam **412** can be suspended from the substrate **414** by a pedestal (not shown).

In FIG. 4b, the multilayer dielectric cladding **100** can be built up from the exterior surfaces **418**, **420**, **424** of the suspended beam **412** by alternating successive depositions of the concentric cladding layers. The multilayer dielectric cladding **100** can comprise the same silicon-based dielectric materials as those described above for the Bragg channel waveguide **300**.

In FIG. 4c, a plurality of holes **426** can be opened in the multilayer dielectric cladding **100** by patterned etching through the cladding layers down to the suspended beam **412**. The holes **426** can be spaced widely to inhibit leakage of the guided light, yet close enough to provide an adequate etch rate for the sacrificial beam material.

In FIG. 4d, the beam **412** can be removed by selective etching of the sacrificial material through the plurality of holes **426** to leave the free-standing Bragg fiber **400**.

FIG. 5 illustrates an exemplary method for fabricating a Bragg fiber **500** using a sacrificial mold. With this method, the Bragg fiber is built up from the interior surface of the hollow mold. A structural hollow tube **528** can formed on the interior surface of a mold-forming trench **512** in a substrate **514**. The substrate **514** can be removed from the tube **528** and the multilayer dielectric cladding **100** can then be deposited on the inner and/or outer wall of the tube **528**.

In FIG. 5a, the trench **512** can first be formed in the substrate **514**. The trench **512** can be rectangular or alternative geometric cross-section, depending on the etching process used and the substrate material. The substrate **514** can be single crystal silicon, gallium arsenide, or other suitable mold-forming material. The trench **512** can be formed by wet or dry chemical

etching of the substrate **514**. For example, a rectangular trench **512** can be formed by reactive ion etching.

In FIG. 5b, the trench **512** can be lined with a thin layer **516** of a structural material which can form the bottom and sidewalls of the tube **528**. The structural material can preferably be SiN. SiN has superior chemical and mechanical properties, has highly selective etch rates over SiO_2 and Si in many etchants, and can be deposited by CVD. SiN also has excellent step coverage for conformal coating of the trench **512**. The thickness of the structural layer **516** can be chosen to satisfy the condition for minimum radiation loss. For example, the SiN layer thickness can be about 0.22 μm for a guided optical wave of 1.55 μm wavelength.

In FIG. 5c, the structural material-lined trench **512** can be backfilled with a sacrificial material **518** to provide a deposit surface **520** for subsequent deposition of a top wall of the tube **528**. The sacrificial material **518** can be polysilicon, deposited from silane by LPCVD. The deposit surface **520** of the sacrificial material **518** can be planarized back to the structural layer **516** by chemical mechanical polishing or other suitable planarizing method.

In FIG. 5d, a top layer **522** of a structural material can then be blanket deposited on the deposit surface **520** and the exposed portion of the structural layer **516**. The portion of the top layer **522** covering the deposit surface **520** will form the top wall of the tube **528**. The structural material and the thickness of the top-wall-forming layer **522** are preferably the same as the bottom- and sidewall-forming layer **516** lining the trench **512**. Thus, the top layer **522** can be SiN having the same thickness as the SiN bottom and sidewall layers (e.g., about 0.22 μm).

In FIG. 5e, a plurality of spaced etch holes **524** can then be opened in the top layer **522** overlying the deposit surface **520** by patterned etching to expose the underlying sacrificial material **518**. The sacrificial material **518** can then be removed from the structural material-lined trench **512** by selective etching through the holes **524**. For example, poly-Si sacrificial material **518**

can be removed from a SiN-lined trench **512** with a highly selective potassium hydroxide (KOH) or tetramethylammonium hydroxide (TMAH) etch.

In FIG. 5f, the structural top layer **522** can then be patterned down to the substrate **514** to leave the portion of the top layer that forms the top wall of the tube **528**.

In FIG. 5g, the substrate **514** surrounding the structural layer **516** can then be removed to leave a hollow tube **528** of the structural material. For example, a silicon substrate **514** can be removed from a SiN tube **528** using a mostly isotropic fluorine-based etch (alternatively, a KOH etch can be used).

In FIG. 5h, the rest of the multilayer dielectric cladding **100** can then be built up by depositing alternating concentric layers of the dielectric cladding materials on the tube **528** to form the Bragg fiber **500**. The alternating cladding layers can have thicknesses that satisfy the condition for minimum radiation loss. The alternating cladding layers can be deposited symmetrically both on the outer wall of the tube **528** and on the inner wall, through the spaced holes **524**, so that two cladding layers of the same dielectric material can be deposited in a single process step.

The free-standing Bragg fiber may be preferred for optical switching applications wherein movement of the waveguide can be desirable. An actuation layer (not shown) can be deposited on the outside of the Bragg fiber **400**, **500** to provide for actuated movement thereof. The actuation layer can be a thin layer of Al or other metal deposited by e-beam processes on the top of the top wall of the Bragg fiber **400**, **500**.

For integrated microphotonics applications, interconnection of optical components can be an important packaging issue. A reflective coupler is commonly used to couple light into or out of an optical waveguide or fiber. Light can be coupled into the Bragg waveguide **300**, **400**, **500** either from the side or from the top. Top coupling can be achieved, for example, by using a 45 degree mirror to reflect light from a direction perpendicular to the propagation axis into the axis of the waveguide. The 45 degree mirror can be fabricated using a wet oxide process whereby a thin, fast-etching oxide is deposited over a slow-etching

oxide. When such mixed-oxide structures are patterned and etched a stable straight slope can be achieved. The slope depends on the ratio of the etch rates of the oxides. Top coupling may improve the density of waveguide packing. Alternatively, moveable micromirrors can be fabricated by MEMS technologies to actively control light coupling into the waveguide.

FIG. 6a shows a scanning electron micrograph of a microfabricated Bragg channel waveguide **300**, comprising a Si/SiN multilayer cladding **100**. The approximately half-cylindrical, 15 μm diameter trench **318** was formed by isotropic reactive ion etching of a silicon substrate **314** through a 2 μm wide etch slot **316** in a SiN/SiO_2 structure mask layer **312**. A thick (about 2 μm thickness) layer **320** of poly-Si was deposited in the etched trench **318** to seal the etch slot **316**. A 1 μm thick layer of thermal oxide **322** was grown on the poly-Si layer to smooth the sidewalls of the trench **318**. A Si/SiN multilayer cladding **100** was formed by CVD of the Si and SiN cladding layers on the inner wall of the trench **316** through spaced gas inlets (not shown).

FIG. 6b shows the microstructure of the Si/SiN multilayer dielectric cladding **100**, comprising alternating thin cladding layers of poly-Si and SiN. The thicknesses of the cladding layers were chosen to minimize the radiation loss for guided light of 1.55 μm wavelength. The thickness of the inner-most first cladding layer **101** of poly-Si is about 0.22 μm. The remaining interior poly-Si cladding layers **103** are about 0.11 μm in thickness. The SiN cladding layers **102**, **104** are about 0.22 μm in thickness.

FIG. 7 shows transmission spectra for Bragg channel waveguides **300** having Si/SiN multilayer claddings **100**. The shortest waveguide, having a length of 300 μm, shows good transmission for guided waves having wavelengths of about 1.58 μm to in excess of 1.69 μm, indicating high reflectivity of the Si/SiN multilayer cladding **100** for this bandwidth. As expected, optical transmission decreases in longer waveguides. From these transmission spectra, the attenuation of this unoptimized Bragg channel waveguide at 1.65 μm wavelength was calculated to be about 8 dB/cm. Attenuations approaching the theoretical

values have been obtained for Bragg waveguides fabricated using the above-described methods and materials for guided optical waves having a range of wavelengths.

The embodiments of the present invention have been described as microfabricated Bragg waveguides and methods for fabricating the Bragg waveguides either as a hollow channel waveguide or as a hollow fiber. It will be understood that the above description is merely illustrative of the applications of the principles of the present invention, the scope of which is to be determined by the claims viewed in light of the specification. Other variants and modifications of the invention will be apparent to those of skill in the art.